RLV TURBINE PERFORMANCE OPTIMIZATION

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ABSTRACT

A task was developed at NASA/Marshall Space Flight Center (MSFC) to improve turbine aerodynamic performance through the application of advanced design and analysis tools. There are four major objectives of this task: 1) to develop, enhance, and integrate advanced turbine aerodynamic design and analysis tools; 2) to develop the methodology for application of the analytical techniques; 3) to demonstrate the benefits of the advanced turbine design procedure through its application to a relevant turbine design point; and 4) to verify the optimized design and analysis with testing. Final results of the preliminary design and the results of the two-dimensional (2D) detailed design of the first-stage vane of a supersonic turbine suitable for a reusable launch vehicle (RLV) are presented. Analytical techniques for obtaining the results are also discussed.

INTRODUCTION

Turbine performance strongly impacts engine specific impulse (Isp), thrust-to-weight, and reliability. This is true regardless of the engine cycle. The capability to optimize designs for performance and robustness leads to increased engine thrust-to-weight, Isp, and reliability thereby reducing system cost and risk. As an example, consider an engine that utilizes a gas generator cycle currently under development for an RLV.

The engine under consideration is required to produce a high value of Isp and a high thrust-to-weight ratio. These requirements have necessitated compact, high power turbine designs. Turbine power is produced through a combination of its mass flow rate and work per pound of fluid. For a gas generator cycle, the propellant is tapped off of the main engine flow to provide the drive gas for the turbine. At the exit of the turbine, the drive gas is dumped overboard and does not significantly contribute to engine thrust. Therefore, for a gas generator cycle, the mass flow rate through the turbine is a direct loss to engine I_{sp} and must be minimized, and power must be produced predominately through high work. There are two options available to obtain the required high work: increasing the available energy of the gas or extracting energy from the gas more efficiently. If the first option is chosen, the turbine inlet temperature would be so high that ceramic materials would be needed for the turbine, since uncooled metals cannot withstand the high temperature. The viability of the ceramic turbine for the application is unproven. Now, consider the option of increasing turbine efficiency. If the turbine work is held constant, a reduction in turbine temperature is directly proportional to the efficiency increase. Reduced temperature would allow the possibility of an uncooled metal turbine. Alternatively, if the ceramic turbine technology is successful, increased efficiency can be used to reduce the mass flow rate. If efficiency is increased by 8 points, mass flow rate can be reduced by approximately 10 percent, and engine Isp is increased by more than 1 second. The increase in Isp corresponds to more than 1500 lbm of payload.

A task was developed with the overall goal of demonstrating the benefits of advanced analytical design and analysis tools in the improvement of turbine aerodynamic performance. There are four major objectives of this task: 1) to develop, enhance, and integrate advanced turbine aerodynamic design and analysis tools; 2) to develop the methodology for application of the analytical techniques; 3) to demonstrate the benefits of the advanced turbine design procedure through its application to a relevant turbine design point: and 4) to verify the optimized design and analysis with testing. The turbine for the RLV discussed is a supersonic design. The hot gas path will be redesigned to obtain an increased

efficiency of at least 8 points. Both preliminary and detailed designs are considered. The preliminary design has been completed and is presented in this paper. The detailed design is in progress, and, as an example, the 2D optimization of the first stage vane is discussed. The redesign of the turbine is conducted with a consideration of system requirements, realizing that a highly efficient turbine that, for example, significantly increases engine weight, is of limited benefit.

APPROACH

The redesign of the turbine was divided into two parts, preliminary design and detailed design. In preliminary design, the overall sizing (e.g., diameter and chords) and performance variables (e.g., speed and reaction) were considered. In detailed design, the detailed shapes of the turbine vanes and blades, the final sizing and performance, and clearances were chosen. The design and analysis procedures used for both types of designs are discussed below.

Preliminary Design

To generate an optimum preliminary design, a systematic application of response surface methodology (RSM) computationally coupled to a meanline analysis was employed. A meanline analysis is a one-dimensional (1D) analysis that employs loss correlations gleaned from experimental databases. This type of analysis, applied at the mean section of the turbine, predicts performance, calculates gas conditions and velocity triangles, and generates a flowpath elevation. It also provides an initial spanwise distribution of row exit angle based on the assumption of constant axial velocity and conservation of angular momentum. A meanline code was developed for this task to provide quick, accurate predictions and was integrated with the optimizer. This code also provides an estimate of turbopump weight. The time required to run the meanline analysis per design point is less than one second, enabling the analysis of a large parametric design space.

To optimize the preliminary design, an approach based on RSM was employed [1]. The design of experiments (DOE) technique called face centered composite design (FCCD) was used to prescribe a set of design points. Numerical results from the meanline analyses of this set of points were used to populate the design space. Second-order polynomials were used to approximate the response surface, creating a global approximation of the variable to be optimized for the prescribed design space. The equation describing the response surface is interrogated to find the maximum or minimum of the chosen variable or function within given constraints. The details of the optimization procedure are given by Papila, *et al* [2].

Detailed Design

To generate an optimum detailed design, computational fluid dynamics (CFD), RSM, and neural nets are used. Ideally, the detailed optimization would be conducted in one step with all rows optimized simultaneously. However, the sheer number of design variables made this approach impractical. Therefore, the detailed design was broken into steps. The first step is to generate and optimize the mean airfoil contours. The DOE technique called orthogonal array design [3] was used to select the set of design points to be analyzed for each airfoil. Unfortunately, some of the design points yielded completely unusable airfoils. To increase the number of points available to generate the response surface, neural nets were trained with the CFD analysis of the usable design points. Both second-order and third-order polynomials were used to approximate the response surface with the third-order polynomials yielding slightly better results. Airfoils were generated using a geometry generator developed for this task that could read a matrix of design variables, generate and plot the airfoil, and write a "first-cut" input file for the CFD grid generator. Unfortunately, as the airfoil shapes varied greatly over the design space, the "first cut" template was inadequate more often than not.

Because a large amount of loss in a supersonic turbine can be attributed to interactions between the first two rows, unsteady CFD calculations were performed for the stage, running parametrics on the vane first with the baseline blade, and then performing the blade parametrics with an optimized vane. Calculations were performed using Wildcat, a parallelized, unsteady, quasi three-dimensional (3D) Navier-Stokes code that utilizes moving grids to simulate rotor motion. Further information on the numerical procedure can be found in Dorney and Verdon [4] and Griffin and Dorney [5].

The next step is to generate the 3D vanes and blades. As a starting point, the vanes and blades will be twisted according to the spanwise angle distribution generated by the meanline analysis. The 3D multistage turbine will be analyzed with Corsair, a parallelized, unsteady, 3D Navier-Stokes code, which has a numerical methodology similar to the quasi-3D code, Wildcat. Based on these results, root and tip sections will be optimized for performance. The final step will be to optimize the axial spacing between rows to reduce unsteady blade loads while maintaining or enhancing efficiency within size constraints.

RESULTS AND DISCUSSION

Preliminary Design

Preliminary design variables to be optimized were chosen as those that had a first order effect on performance. Design variables along with their ranges are shown in Tables 1 a-c. Distinct optimizations were performed for each number-of-stages case, 1, 2, or 3. Inlet total pressure, total-to-static pressure ratio, inlet total temperature, and mass flow rate were held constant for all design points. Two design constraints were imposed: a limit on AN^2 (flow area times the square of the wheel speed), an indication of blade centrifugal stress, and a limit on the pitchline velocity, an indication of disk structural burst limit.

Design Variable	Lower Limit	Upper Limit
Mean Diameter	0.5	1.5
Speed	0.7	1.3
Blade Annulus Area	0.7	1.3
Vane Axial Chord	0.4	1.7
Blade Axial Chord	0.3	1.1
Reaction	0.0	0.5

a) 1 Stage

Design Variable	Lower Limit	Upper Limit
1st Blade Height	0.9	1.5
2nd Vane Axial Chord	0.3	1.8
2nd Blade Axial Chord	0.2	1.1
2nd Stage Reaction	0.0	0.5
Work Fraction(1st Stg)	0.5	0.85

b) 2 Stage Additional Variables

Design Variable	Lower Limit	Upper Limit
3rd Vane Axial Chord	0.2	1.4
3rd Blade Axial Chord	0.2	1.1
2nd Stage Reaction	0.0	0.5
Work Fraction(1st Stg)	0.4	0.8
Work Fraction (2nd Stg)	0.1	0.3

c) 3 Stage Additional Variables

Table 1. Preliminary Design Variables and Ranges (all variables normalized by baseline values except for reaction and work fraction)

Three sets of optimizations were performed. In the first set, the objective function was chosen to be total-to-static turbine efficiency. In the second set, the objective function was chosen to be turbopump weight. In the third set, the payload capacity, a function of efficiency and weight, was optimized. A function to correlate turbine efficiency and turbopump weight was derived from system models. Plots of the results are shown in Figs. 1 a-c. Figure 1a shows efficiency versus number of stages. The three curves on the figure represent the efficiency for each number of stages when optimized for 1) maximum efficiency, 2) minimum weight, and 3) maximum payload capacity. As can be seen from this chart, the maximum efficiency occurred for a three stage turbine optimized for efficiency, showing an increase in efficiency over the baseline of about 15 points. Figure 1b shows weight versus number of stages. This chart shows that the minimum weight occurred for a single-stage turbine optimized for weight, reducing weight per turbopump by approximately 550 lbs. Note that the three-stage turbine optimized for efficiency is the heaviest of the optimized designs. Also note that the single stage turbine optimized for weight has the poorest efficiency. In Fig 1c, a plot of payload versus number of stages is shown. The maximum increase in payload occurred for a two-stage turbine using the composite response surface of efficiency and weight, showing an increase in payload capacity of approximately 700 lbs per turbopump. With the consideration of the system in mind, the preliminary design was chosen as the design optimized for payload capacity. Table 2 shows the optimized design variables. The optimized design has a predicted increase in total-to-total efficiency of approximately 9 points over the baseline.

Design Variable	Value
Mean Diameter	1.12
Speed	1.02
Exit Annulus Area	1.08
1st Blade Height	1.50
1st Vane Axial Chord	1.30
2nd Vane Axial Chord	0.79
1st Blade Axial Chord	0.71
2nd Blade Axial Chord	0.62
Reaction (1st Stg)	0.10
Reaction (2nd Stg)	0.50
Work Fraction (1st Stg)	0.90

Table 2. Optimized Preliminary Design (all variables normalized by baseline values except for reaction and work fraction)

Figure 2 shows the percentage of the performance increase attributed to the change in each design variable. The most significant variables are shown to be diameter, areas, and chords, indicating increases in velocity ratio and aspect ratio. Figure 3 shows a breakdown of the losses in the optimized preliminary design, where 1-Phi^2 is an indication of loss. As this plot shows baseline loss minus optimized design loss, a positive value indicates reduced loss. Most of the loss reduction is predicted to be due to lower secondary losses. This correlates well with the increases in velocity ratio and aspect ratios.

Detailed Design

The baseline supersonic turbine was analyzed using Corsair. The numerical methodology is similar to the quasi-3D code, Wildcat. The CFD predicted efficiency was within two points of the meanline design code. Predicted instantaneous Mach contours are shown in Fig. 4. This plot shows some of the undesirable, although generally unavoidable, features of a supersonic turbine. The first stage nozzle is a converging-diverging nozzle of rectangular cross-section. This design is lower performing than a vane, but is typically cheaper to manufacture. The shock at the leading edge of the first blade is strong enough

to separate the boundary layer on the suction side of the blade. Strong interactions between the nozzle and blade exist, generating additional loss. These flow features were considered as the design variables and ranges were chosen.

Using current design procedures, a second-generation detailed design was developed for the flow conditions predicted for the optimized preliminary design. This design was used to gauge improvements when optimizing the airfoil rows. Detailed design variables were chosen as those that had the most impact on the airfoil contour, namely the pressure side height/axial chord (H/L), uncovered turning, and 5 Bezier control handles (Fig. 5) for the first vane. The variable ranges are shown in Table 3. Constraints for minimum thickness, minimum curvature, and curvature distribution were developed and imposed. Two hundred-fourteen cases were selected as design points. Of these design points, 10 airfoils were unusable. The remaining cases were analyzed using Wildcat. The stage had a vane-to-blade ratio of 12 to 30, was scaled to a 15 to 30 ratio, and analyzed as 1 vane to 2 blades. Grid densities and distributions were chosen to achieve an average y^+ value of the first point off the wall less than 1, 15 points in the boundary layer, and to ensure that the wakes were convected from one row to the next. Each case was run on one processor of an SGI computer (Origin 2000, Power Challenge, or Octane). Because of the strong interactions between vane and blade, it was sometimes difficult to attribute some of the losses distinctly to the vane or the blade. Therefore, stage total-to-total efficiency was chosen as the objective function. Performing the analyses of the usable airfoils took approximately 1 1/2 weeks of wall clock time. Times per calculation varied depending on which SGI computer had available processors.

Design Variable	Lower Limit	Upper Limit
H/L	0.79	1.19
Uncovered Turning	-1.20	-0.20
L1	0.36	2.00
L3F	0.44	1.76
L3R	0.25	2.00
L4	0.05	1.25
L5	0.13	2.00

Table 3 Detailed Design Space (variables normalized by baseline values)

Results from the CFD analyses of the design space indicated that the highest performing vanes had a low value of H/L and a high (less negative) value of uncovered turning. Trends in the other variables were not apparent. Three optimization cycles were employed. In cycle 1, second and third order polynomials were used to approximate the response surface. In cycle 2, the ranges on L4 and L5 were extended. In cycle 3, neural nets were used to generate additional points with which to create the response surface. Predicted optimum designs were analyzed with Wildcat, and indicated that that each cycle produced reasonable results with the third generation having the highest accuracy. Considering that changes in efficiency from one design to the next could be very small, a high degree of accuracy was needed for this task, and the results from the third generation were chosen. The predicted optimum design variables are shown in Table 4. The variables tend toward their limits. The design space could be expanded to investigate whether a more efficient design existed beyond the design space. However, due to time constraints, the design space was only extended for variables L4 and L5. Investigation of the results from the optimization showed that in the region of the response surface where the efficiency was highest, the surface was relatively flat with respect to L4 and L5. The ranges for these two variables were extended, and additional CFD analyses were performed. Results indicated that for the optimum combination of the other design variables, the choice of L4 and L5 had little effect on efficiency. Therefore, for structural considerations, L5 was chosen to give a thicker airfoil than suggested by the optimizer (Fig. 6). As the suction surface is nearly straight approaching the trailing edge, changes in L4 have little effect on the contour. Figure 7 shows instantaneous Mach numbers for the thicker airfoil. As the Mach numbers on the pressure side of the airfoil are so low, the slight increase in Mach number due to the thicker airfoil

does not significantly increase losses. The stage efficiency with the optimized vane was predicted to be 3.2 points higher than the baseline. The exact reason for the improvement in performance is unknown at this time, and is being investigated. The base drag appears to be lower for the optimized vane, although it is not clear why this is so.

Design Variable	Value
H/L	0.79
Uncovered Turning	-0.20
L1	2.00
L3F	0.44
L3R	2.00
L4	1.35
L5	2.50

Table 4 Optimized Mean Section of 1st Vane (values normalized by baseline values)

SUMMARY/CONCLUSIONS

A task to improve turbine performance through the application of advanced design techniques has been developed. Advanced design and analysis tools and techniques have been applied to the preliminary and detailed design of an RLV supersonic turbine with the goal of demonstrating an efficiency improvement of 8 points. The preliminary design is completed, and the 2D optimization is nearing completion. Results from the preliminary design optimization and the 2D optimization of the first vane were presented. The efficiency goal has been predicted to be exceeded in the preliminary and 2D detailed design. Currently, the results are being interrogated to determine the mechanisms of the performance improvements. Continued improvements will be made through 3D considerations of exit angle distribution and axial spacing. Unsteady aspects of the flow will also be considered. The final design will be highly instrumented and tested in air.

From this work, some observations can be made about the design procedure. Global optimization is a good technique to gain understanding of a complete design space. The understanding of the complete space allows trades to be made when selecting an "optimum design". This can be very important in allowing options in the selection of a final design when the optimization is not performed in a multidisciplinary setting, as seen in the choice of a thicker vane in this study, or when design constraints are not fully developed or understood. However, the RSM requires large amounts of data to begin the optimization of the design. In addition, the more design variables considered, the more data is required (known as the "curse of dimensionality"). In order to be efficiently used, more automation of the procedure and coupling of the codes from design point selection, to meanline analysis, geometry generation, CFD analysis, and optimization is needed. For detailed design, neural nets to enhance the data supplied to the RSM appear to be necessary for turbine detailed design. The neural nets are needed to allow a better representation of the design space and to reduce the required number of CFD calculations. Efforts to improve the run time efficiency of the CFD codes are necessary, as has been done with Wildcat and Corsair. An efficient, accurate procedure will allow the designer to consider a larger design space than currently considered.

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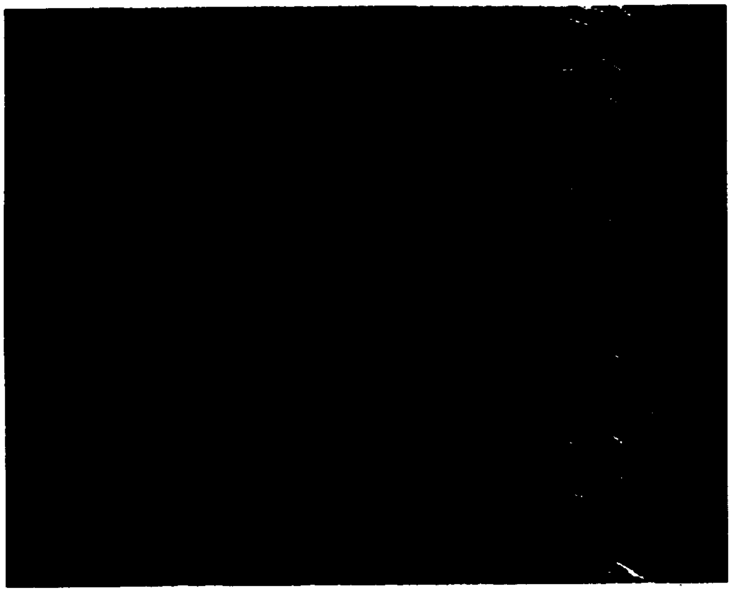

Fig. 4 Predicted Mach Number Contours for Baseline Turbine

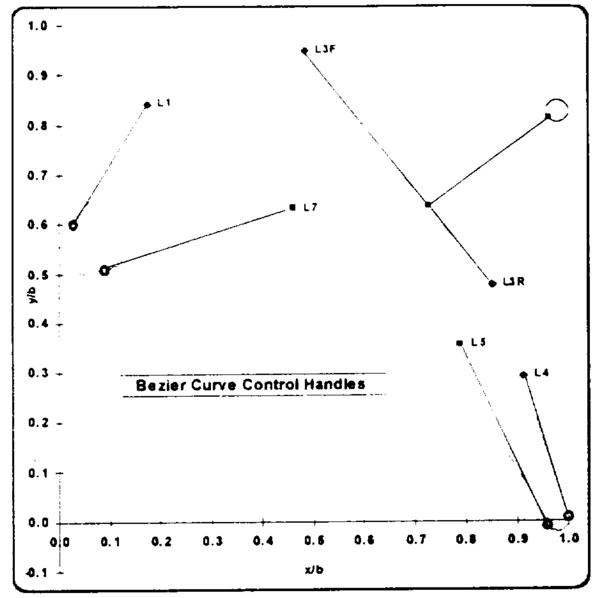

Fig. 5 Bezier Control Handles

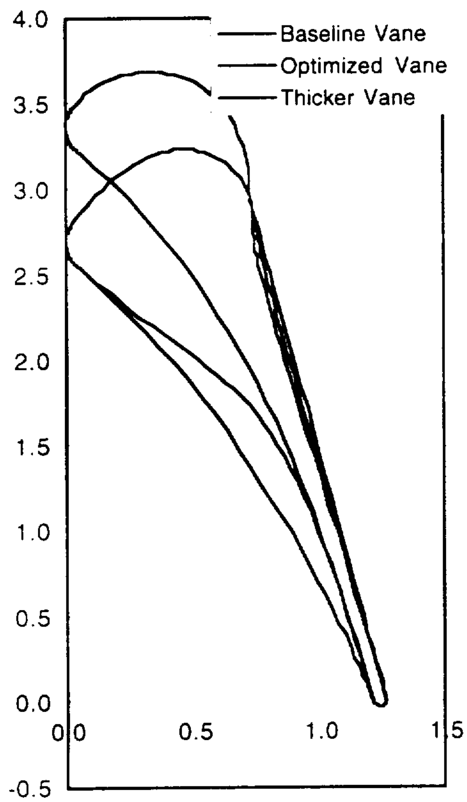

Fig. 6 Optimized Vane Shapes

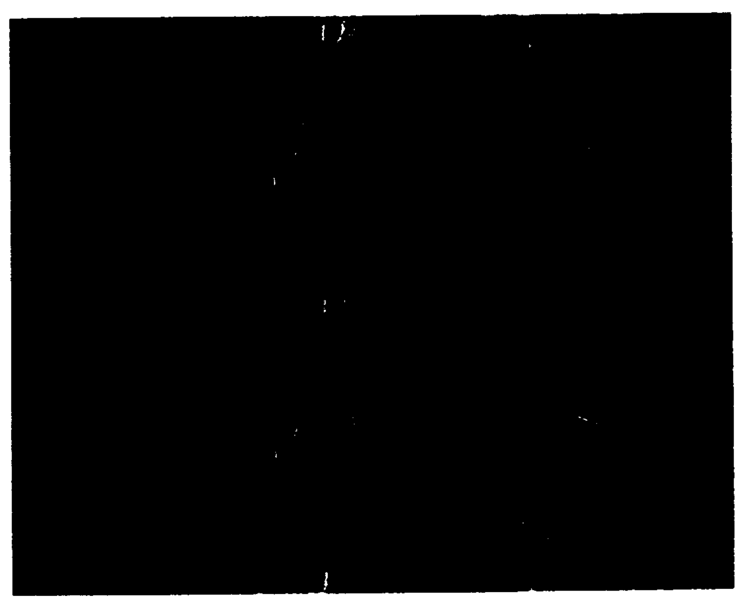

Fig. 7 Instantaneous Mach Numbers for Optimized Vane

of turbine aerodynamic design knowledge. Wei Shyy and Nilay Papila of the University of Florida developed the optimization procedures and performed the design optimizations. This work has been funded by the Advanced Space Transportation Program at NASA/MSFC through NRA 8-21. The authors are very appreciative of the support provided for this task, particularly by Shayne Swint, the project manager at MSFC.

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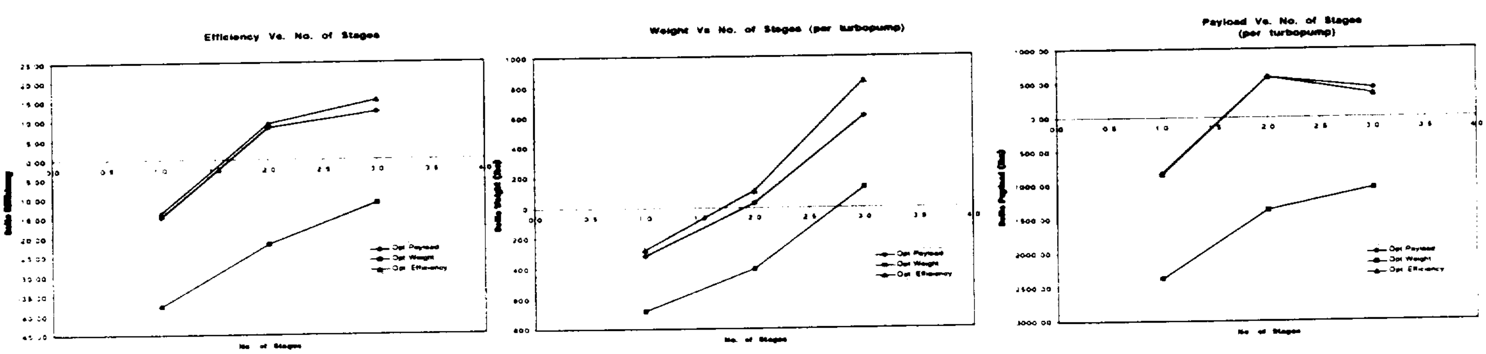

(a) (b) (c)

Fig. 1 Preliminary Design Optimization

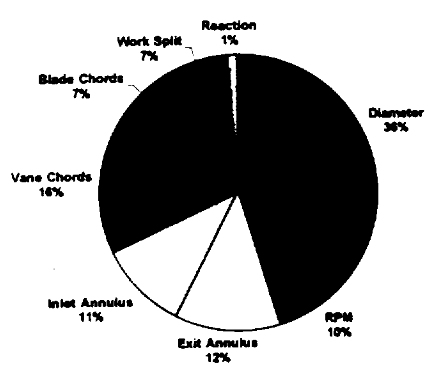

Fig. 2 Influence of Design Variables

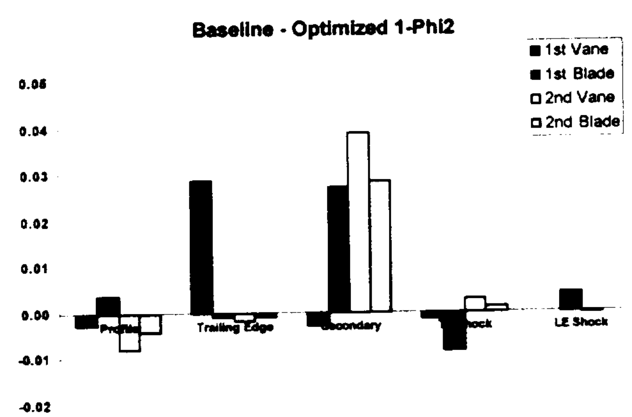

Fig 3. Breakdown of Losses